The University of Sydney
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# Metamorphic and geochronological evolution of the Kemp and MacRobertson Land coast, east Antarctica

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## Declaration

I declare that this thesis is less than 100 000 words in length and that the work contained in this thesis has not been submitted for a higher degree at any other university or institution.

Jacqueline A. Halpin
February 2007

## Preface

This thesis contains a collection of journal articles that are published, under review or prepared for submission to international peer-reviewed journals of geology (below). These four publications develop fundamental themes integral to this thesis and are presented in an order which maintains a cohesive progression and builds upon proceeding work. An introductory section outlines the aims and scope of the thesis and summarises the contributions to the field of geology. Common themes from the research papers are examined in a discussion chapter and the main conclusions are summarised at the end.

This thesis is based on the following four papers, referred to by their Roman numbers:

*Paper I* Halpin JA, Gerakiteys CL, Clarke GL, Belousova EA, Griffin WL (2005) In situ U-Pb geochronology and Hf isotope analyses of the Rayner Complex, east Antarctica. Contributions to Mineralogy and Petrology 148: 689 – 107

*Paper II* Halpin JA, White RW, Clarke GL, Kelsey DE (in review) The Proterozoic P-T-t evolution of the Kemp Land coast, east Antarctica; constraints from Si-saturated and Si-undersaturated metapelites. Journal of Petrology

*Paper III* Halpin JA, Clarke GL, White RW, Kelsey DE (submitted) Contrasting P-T-t paths for Neoproterozoic metamorphism in MacRobertson and Kemp Lands, east Antarctica. Journal of Metamorphic Geology

*Paper IV* Halpin JA, Clarke GL, White RW (in progress) Evolution of the Stillwell Hills, Rayner Complex, east Antarctica; a reworked cratonic margin

Work published in this thesis has been presented at two international conferences under the following abstracts:

Halpin JA, Gerakiteys CL, Clarke GL, Belousova EA, Griffin WL (2005) In situ U-Pb geochronology and Hf isotope analyses of the Rayner Complex, east Antarctica. Goldschmidt Conference Abstracts, Geochimica et Cosmochimica Acta, 69(10) Supplement 1:pp. 829

Halpin, JA, Clarke, GL, White RW (2006) Contrasting Rayner Structural Episode metamorphism in Kemp and MacRobertson Lands: evidence for a Neoproterozoic terrane boundary? 2nd SCAR Open Science Conference Abstracts, A410

No animal or ethical approvals were required during the completion of this study. Fieldwork in Antarctica was undertaken in accordance with the 'Environmental Code of Conduct for Australian Field Activities in Antarctica' (www.aad.gov.au). Appropriate permits were obtained for the collection of samples. Data and interpretations in this thesis are the work of the author unless stated.

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I'd hoped it would happen at some point, but finishing a thesis always seemed like something that happened to other people! I would never have got to this stage without the help of my supervisors Geoff Clarke and Dick White who introduced me to the world of metamorphic rocks (the pretty, sparkly and properly-hot ones) and kept me on track when things went pear-shaped, as they inevitably do – I've learnt so much, laughed a great deal and shared a fantastic four years with you both.

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## Contents

# Abstract

Rocks of the Kemp and MacRobertson Land coastline, east Antarctica, expose a semi-continuous profile through the middle- to lower-crustal sections of a Neoproterozoic convergent orogen called the Rayner Complex. Kemp Land exposures are dominated by Archaean felsic orthogneiss interpreted to represent the tectonically reworked margin of a continental fragment called the Napier Complex, whereas MacRobertson Land exposures are dominated by supracrustal successions of probable Proterozoic age and voluminous felsic plutonic rocks. All of these rocks were deformed and metamorphosed at granulite facies conditions during the *ca.* 1000 – 900 Ma Rayner Structural Episode, which was a consequence of the convergence of crustal blocks that now constitute extensive parts of eastern India and east Antarctica, and formed part of the supercontinent called Rodinia. This thesis examines the geochronological, metamorphic and structural evolution of the Kemp and MacRobertson Land rocks and focuses on two main themes: (1) the Archaean and early Proterozoic history of continental crust before the Rayner Structural Episode as preserved in Kemp Land exposures; and (2) syn-orogenic processes related to the Rayner Structural Episode which affected all rocks along the coast, and implications for the tectonic evolution of the Rayner Complex.

Exposures in Kemp Land, which includes parts of both the Napier (Rippon Point) and Rayner (Oygarden Group, Broka and Havstein Islands, Stillwell Hills) Complexes, are dominated by layered Archaean orthogneiss. On the basis of *in situ* zircon U-Pb and Hf isotopic analysis, precursors to this orthogneiss were emplaced before *ca.* 3650 – 3500 Ma and involved significant melting of *ca.* 3900 – 3700 Ma crustal material with input from primary *ca.* 3600 Ma mantle melts. Plausible protoliths include *ca.* 3800 Ma orthogneiss exposed in the Tula Mountains in the Napier Complex. Evidence for a pervasive *ca.* 2470 Ma tectonothermal event is preserved in rocks from most of western Kemp Land and the western Napier Complex. These isotopic data suggest Kemp Land was part of the eastern Napier Complex after *ca.* 3500 Ma, and part of the greater Napier Craton at, or before, *ca.* 2470 Ma. Charnockite was emplaced in the Stillwell Hills region prior to *ca.* 1620 Ma and represents post-Archaean crustal addition to Kemp Land. Source magmas are likely to have involved some juvenile material and the reworking of a *ca.* 2600 Ma lower crust. The *ca.* 980 Ma Mawson Charnockite exposed in MacRobertson Land was sourced from *ca.* 2100 Ma lower crustal protoliths, without significant addition of juvenile magmas. The zircon U-Pb and Hf isotopic data distinguish at least two terranes: a crustal block dominated by Archaean rock in Kemp Land, and a crustal block dominated by comparatively juvenile Proterozoic rock in MacRobertson Land. Much of the Kemp Land terrane represents a part of the Napier Complex that was tectonically reworked during the Neoproterozoic. Rocks to the east of the Stillwell Hills form the MacRobertson Land terrane and represent Proterozoic crust accreted to a complexly deformed Kemp-Napier Archaean craton after *ca.* 1600 Ma. Any incorporation of juvenile material during orogenesis was minor, indicating that this part of the Rayner Complex consists mainly of ensialic crust.

The effects of plate convergence related to the Rayner Structural Episode were first recorded by juvenile metasediments in MacRobertson Land. A shallowly-dipping high-grade gneissosity developed at *ca.* 995 – 970 Ma, contemporary with peak metamorphic conditions. Well-developed mineral microstructures in metapelitic gneiss from Cape Bruce and the Forbes Glacier along the Mawson Coast record heating to $T \approx 850 – 920$ ˚C at $P \approx 5.4 – 6.2$ kbar. Syn-orogenic felsic granitoids, including voluminous charnockitic magma, were emplaced during continued deformation. This magma flux is interpreted to have maintained elevated temperatures at a regional scale; advection was accompanied by crustal thickening to maximum pressures of $P \approx 6.0 – 6.8$ kbar. Mineral reaction textures in metasedimentary gneiss, formed during this 'anticlockwise' *P-T-t* path, record near-isobaric cooling and protracted metamorphism over *ca.* 80 Myrs. Diverse metapelitic assemblages from the Stillwell Hills, Broka and Havstein Islands and the Oygarden Group in Kemp Land record *ca.* 940 – 930 Ma peak metamorphic conditions that involved $T \approx 870 – 990$ ˚C at $P \approx 7.4 – 10$ kbar, with pressure conditions increasing westward towards the Napier Complex. A penetrative sub-horizontal gneissosity formed in these high-*P*, high-*T* rocks some 30 – 60 Myrs after equivalent features formed in lower-*P* rocks in MacRobertson Land. Mineral reaction textures in Kemp Land rocks define a decompressive-cooling trajectory ($dP/dT \approx 17$ bar/˚C), which is part of a 'clockwise' *P-T-t* path that documents uplift and cooling of the Napier cratonic margin over *ca.* 25 Myrs. The contrast in the *P-T-t* paths recorded by the adjacent terranes, coupled with the spatial variation in the style and intensity of deformation, is likely to reflect the effects of intense strain partitioning and spatially focussed

magmatism across the collisional margin. Initial penetrative deformation is inferred to have been accompanied by syn-orogenic magmatic doming in the internal portions of the orogen (MacRobertson Land), while the tectonic reworking of older, anhydrous parts of the crust closer to the orogenic front (Kemp Land) occurred during the waning stages of orogenesis. This later phase of convergence associated with the involvement of the Kemp Land terrane may have made a dynamic contribution to the prevailing tectonic framework, indicated by a change in the style of deformation that occurred across several locations in MacRobertson Land at *ca.* 940 – 900 Ma.

Geological relationships in the Stillwell Hills region, which lies at the eastern margin of tectonically reworked Archaean crust, reflect both the pre- and syn-orogenic evolution of the Rayner Complex. Layered orthogneiss preserves evidence for two high-grade fabrics which developed during at least two deformational events ($D_1$ and $D_2$) prior to *ca*. 1620 Ma. Correlation with high-grade fabrics in rocks further west suggest that the alignment of early leucocratic segregations ($S_1$) may have occurred at *ca.* 3490 – 3400 Ma. The correlation of mafic layers within the layered Archaean orthogneiss with *ca*. 2400 – 2350 Ma mafic dykes in the Napier Complex suggests that the development of the dominant form surface ($S_2$) occurred during the Palaeoproterozoic. $D_1$ and $D_2$ suggest that significant dehydration of the Kemp Land terrane occurred prior to the Rayner Structural Episode. Penetrative deformation at mid- to lower-crustal levels at *ca*. 945 Ma involved the development of a pervasive sub-horizontal $S_3$ gneissosity and inclined to recumbent $F_3$ folds. North-trending $F_3$ fold axes rotate towards the east in areas of high strain, consistent with strain having accumulated from progressive simple shear. $D_3$ structures are invariably overprinted by $D_4$ and $D_5$ dome and basin-type folding. North to northeast-trending upright to inclined $F_4$ folds are sub-parallel to $F_3$ folds; both fold generations are inferred to have developed during west-directed ductile thrusting of the Napier cratonic margin. $D_3$ and $D_4$ structures were reorientated about east to southeast-trending $F_5$ folds during the waning stages of orogenesis. Late Neoproterozoic to early Palaeoproterozoic $D_6$ mylonitic shear zones cross-cut all ductile structures and reflect north-directed intraplate deformation.

Charnockitic magmatism at *ca*. 1620 Ma in the Stillwell Hills reflects a significant tectonothermal event during the late Palaeoproterozoic in this region of east Antarctica. The correlation of the Kemp and MacRobertson Land rocks with equivalent late Palaeoproterozoic granulite facies rocks in the southern Eastern Ghats Belt (India) suggests that the Kemp-Napier Craton may have collided with the eastern Dharwar Craton at this time. An amalgamated Kemp-Napier-eastern India crustal block presents a plausible continental shield for the accretion of crustal fragments now comprising the Rayner Complex in MacRobertson Land and the central and northern Eastern Ghats Belt during the Meso-Neoproterozoic. This scenario is consistent with an active continental margin setting at *ca.* 1600 Ma, which may have evolved to continent-continent collision by *ca.* 1000 Ma. The involvement of the southern and/or eastern (present coordinates) continental block(s) during Neoproterozoic orogenesis remains enigmatic.

Exposed granulite facies terranes provide a valuable window into the earth's lower crust. The origins of granulites, the processes involved in their formation and their role in crustal evolution, continue to invoke rigorous investigation. Recent work attempts to quantitatively integrate petrographic, structural and geochronological studies of high-grade gneisses to unravel complex orogenic processes.

Advances in the analysis of isotopic and chemical systems in accessory minerals and mineral equilibria modelling over the last decade have led to a greater understanding of lower-crustal processes. This study aims to incorporate a number of these recently improved techniques to characterise the evolution of a regionally exposed mobile belt, the Rayner Complex, in east Antarctica. This deeply eroded orogen outcrops along some 300 km of coastline in Kemp and MacRobertson Land and provides a unique opportunity to examine a semi-continuous titled profile through the middle- to lower-crust.

## Thesis scope

This thesis aims to integrate the geochronological, metamorphic and structural evolution of a Neoproterozoic orogen, the Rayner Complex, exposed in rocks along the Kemp and MacRobertson Land coastline. Fundamental to characterisation of the crustal evolution of this mobile belt is an understanding of a complex tectonothermal history, structural relationships, mineral microstructures and quantification of the metamorphic conditions and *P-T-t* paths through which these mid- to lower-crustal rocks evolved. Advancements in these central themes contribute to a greater understanding of granulite facies terranes and ultimately to the evolution of the lower crust. The following interrelated problems are considered in chapters of this thesis, presented as a series of papers:

- To what extent does the Kemp and MacRobertson Land coastline represent Archaean or Proterozoic crust and how old are the likely sources? What is the contribution of juvenile magmas compared with intracrustal reworking? That is, what was the spatial and temporal framework of this multiplely deformed region and what are the implications for crustal evolution?

- What metamorphic conditions are recorded in rocks along the Kemp and MacRobertson Land coasts? Were peak metamorphic conditions reached at the same time along the coastline? What do these conditions imply for the crustal-depth profile across this section of the orogen and the timing of collisional orogenesis?

- Can mineral reaction microstructures in diverse metapelitic assemblages be used to quantitatively constrain the *P-T* trajectory? Did these mineral textures develop during a single metamorphic event?

- What information concerning the exhumation/cooling history of the mid- to lower-crust may be derived from any difference in *P-T-t* paths recorded by various parts of the Rayner Complex? What are the implications for the crustal architecture and what constraints do these *P-T-t* trajectories place on the thermo-physical evolution of the mobile belt?

- What are the structural and geochronological constraints on the evolution of the Stillwell Hills region? How does the structural history relate to that of rocks forming other parts of the Kemp and MacRobertson Land coasts? What are the implications for the tectonic evolution of the Kemp and MacRobertson Land coasts?

- Can revised correlations be drawn between this region of east Antarctica and the east coast of India, proposed counterparts during the formation of Rodinia? What are the implications for the evolution of the mobile belt? What do the revised geochronological, metamorphic and structural constraints imply for the tectonic setting of this convergent margin?

These main objectives form the basis of four research papers and incorporate the use of U-Pb and Lu-Hf isotopic systematics of zircon, (U+Th)-Pb chemical dating of monazite and mineral equilibria modelling which utilises recently expanded chemical systems and new activity-composition relationships. In the context of detailed geological mapping and petrographical and structural analysis, these techniques and data provide a comprehensive basis for integration of the geochronological, structural and metamorphic evolution of a lower-crustal orogen.

## Thesis outline

Field mapping and sampling were conducted along the Kemp and MacRobertson Land coasts in the Australian Antarctic Territory during the 2002 austral spring/summer. The Australian Antarctic Division was unable to support a scheduled second field season in 2003/04, which was postponed until the summer of 2004/05. Unfortunately, aircraft delays and associated logistical problems after our arrival in Antarctica in November 2004 meant this field season was cancelled. As a consequence, work plans were revised and many of the samples used in this work were obtained from an archive at the University of Sydney. U-Pb and Hf isotope analyses were performed at the GEMOC Key Centre at Macquarie University. Cathodoluminescence imagery of zircons was carried out at the University of Technology, Sydney. Microprobe analyses were conducted at the Electron Microprobe Unit at the University of New South Wales and the GEMOC Key Centre at Macquarie University. Monazite analyses were conducted at Adelaide Microscopy at the University of Adelaide. Petrographic and structural analysis was completed at the University of Sydney.

**Paper I** *In situ U-Pb geochronology and Hf isotope analyses of the Rayner Complex, east Antarctica*, addresses the terrane evolution of the poly-tectonothermal Rayner Complex through Laser Ablation Microprobe-Inductively Coupled Plasma Mass Spectrometer (LAM-ICPMS) analyses of zircon. I am first author on this paper of which 100 % can be credited to this thesis. The second author is a past student at the University of Sydney who collected some of the samples and performed initial zircon analyses and the third author is my PhD supervisor whose research grants funded the work and who helped in preparation of the manuscript. The fourth and fifth authors are collaborators from Macquarie University who provided assistance in the LAM-ICPMS data collection and interpretation. The integration of *in situ* analysis of U-Pb and Hf isotopic systems in zircon in this study allows significant insight into the spatial and temporal framework of high-grade rocks exposed along the Kemp and MacRobertson Land coastline. In particular, U-Pb zircon analyses from Archaean orthogneisses in Kemp Land record evidence for several periods of isotopic disturbance and multiple growth stages through the Archaean to Neoproterozoic. Parental melts were derived from intracrustal reworking of a *ca.* 3900 – 3700 Ma protolith with *ca*. 3600 Ma juvenile additions. The recognition of late Palaeoproterozoic charnockite in the Stillwell Hills provides an important link with a *ca*. 1600 Ma thermal event in the Oygarden Group and has regional implications for the correlation of India and east Antarctica. These data confirm relations posited on the basis of field relationships and reconnaissance dating that rocks exposed in Kemp Land represent a tectonically reworked margin of the Napier Craton, and have an evolutionary history distinct to other parts of the Rayner Complex which are likely to comprise a number of Palaeoproterozoic basement terranes accreted to a complexly deformed Archaean craton during the Meso-Neoproterozoic.

**Paper II** *The Proterozoic P-T-t evolution of the Kemp Land coast, east Antarctica; constraints from Si-saturated and Si-undersaturated metapelites,* examines metapelitic assemblages from the Stillwell Hills, Broka and Havstein Islands and the Oygarden Group which developed during pervasive Neoproterozoic metamorphism. I am first author on this paper of which 100 % can be credited to this thesis. The second and third authors are my PhD supervisors whose research grants funded the work and who helped in preparation of the manuscript. The fourth author is a collaborator from the University of Adelaide, who provided assistance with the Electron Microprobe (EMP) monazite analyses and data processing. Calculated *P-T* pseudosections for a suite of metapelites enable the interpretation of peak conditions and a *P-T* trajectory for a series of mineral reaction textures, and *in situ* EMP dating of monazite is used to constrain the age of peak or near-peak metamorphism. This integrated metamorphic and geochronological approach suggests that the mineral assemblages reflect *ca.* 940 – 930 Ma peak conditions involving $T \approx 870 – 990\ ^{\circ}C$ at $P \approx 7.4 – 10$ kbar, with pressure increasing westward towards the Napier Complex. A major outcome of this paper is that the development of post-peak microstructures in both Si-saturated and Si-undersaturated rocks from the Stillwell Hills is consistent with a post-peak decompressive-cooling path. This *P-T-t* path contrasts with steep, near-isothermal decompression *P-T* paths which are generally cited for the region and has implications for tectonic models of the mid- to lower-crustal response to collision during Neoproterozoic orogenesis.

**Paper III** *Contrasting P-T-t paths for Neoproterozoic metamorphism in MacRobertson and Kemp Lands, east Antarctica*, focuses on the metamorphic evolution of metasediments from the Mawson Coast in MacRobertson Land in order to provide a detailed framework for the comparison of the *P-T-t* evolution with the adjacent Kemp Land terrane. I am first author on this paper of which 100 % can be credited to this thesis. The second and third authors are my PhD supervisors whose research grants funded the work and who helped in the preparation of the manuscript. The fourth author is a collaborator from the University of Adelaide who provided assistance with the EMP monazite analyses and data processing. Metapelitic microstructures record an anticlockwise *P-T-t* path involving peak conditions of $T \approx 850 – 920$ ˚C at $P \approx 5.4 – 6.2$ kbar. The onset of collisional tectonics and peak metamorphic conditions in this terrane occurred at *ca.* 990 – 970 Ma, prior to the emplacement of regionally extensive syn-tectonic magmas. An increase in pressure to $P \approx 6.0 – 6.8$ kbar and ensuing near-isobaric cooling occurred over *ca.* 80 Myrs. This protracted metamorphic evolution is in marked contrast to the clockwise *P-T-t* path dominated by decompressive-cooling recorded by the Kemp Land terrane and provides new constraints on the thermo-physical evolution of the Rayner Complex.

**Paper IV** *Evolution of the Stillwell Hills, Rayner Complex, east Antarctica; a reworked cratonic margin*, provides a detailed description of the lithological and structural framework of the Stillwell Hills region in eastern Kemp Land. This region constitutes the eastern margin of the reworked Napier Craton and diverse mineral assemblages record a complex geological history spanning some 2500 Myrs. I am first author on this paper of which 100 % can be credited to this thesis. The second and third authors are my PhD supervisors whose research grants funded the work and who helped in field mapping, sample collection and the preparation of the manuscript. Geological maps included in this work were complied over a number of field seasons and the geologists involved are acknowledged. This paper aims to place geochronological and metamorphic relationships in a structural context to provide a likely tectonic evolution for the Rayner Complex along the Kemp and MacRobertson Land coasts. At least two high-grade tectonothermal events occurred during the Archaean – Palaeoproterozoic in the Kemp Land terrane (local $D_1$ and $D_2$), whereas three events are attributed to collisional tectonics during Neoproterozoic orogenesis ($D_3 – D_5$). The $D_3$ and $D_4$ deformational events involved *ca.* 945 Ma west-directed ductile thrusting of the Napier cratonic margin in eastern Kemp Land. These early structures were reoriented about east-trending folds during the waning stages of orogenesis to produce the regional E-W-trending structural grain in outcrops along the Kemp Land coast. Semi-brittle deformation occurred much later as a response to intra-plate deformation. Correlation of late Palaeoproterozoic metamorphism and magmatism in Kemp Land with tectonothermal activity in the southern Eastern Ghats Belt in India is consistent with an Indo-Antarctic accretionary margin, and the assembly of the Proterozoic terranes in the Rayner Complex in MacRobertson Land and the northern sector of the Eastern Ghats Belt during the Meso-Neoproterozoic. The timing of Neoproterozoic deformation in Kemp Land coincides with a second phase of deformation involving a shift to upright, E-W trending structures in MacRobertson Land, which may be intrinsically linked to the involvement of this Kemp-Napier-southern Eastern Ghats block in collision.

The **Discussion** provides a summary of the important findings allowing for an examination of the Archaean to Neoproterozoic evolution of the Kemp and MacRobertson Land coastline in the wider geological setting. Current theories for the tectonic evolution of the Rayner Complex, together with the Eastern Ghats Belt, are examined and a revised model is proposed. The central themes involved in this thesis contribute to our overall understanding of the evolution of ancient metamorphic terranes and mid- to lower-crustal processes involved in orogenesis.